ROYAL EGYPTIAN INSTITUTION
OF
ENGINEERS

THE PROBLEM OF THE LONG SPAN

BY

Prof. Dr. F. STÜSSI, Dr. sc. techn., Dr. h. c.

Rector of the Swiss Federal Institute of Technology
(E.T.H., Zürich)

LECTURE DELIVERED ON 1st JANUARY 1951 ON THE OCCASSION OF THE 25th ANIVERSARY OF FOUAD I UNIVERSITY

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THE PROBLEM OF THE LONG SPAN

1. The problem of the long span has always fascinated specialists as well as ordinary individuals. The realisation of a bridge with a length of span hitherto unattained, not only requires great technical knowledge and capacity, but also intuition and creative courage; it signifies a victory over the forces of nature and progress in the battle against human insufficiency.

Permit me first of all to elucidate the problem from the human side by a few examples from the history of bridge building and to start by mentioning a Swiss master-builder.

The carpenter, Johann Ulrich Grubenmann (1709-1783), of Teufen, was ordered in 1755 by the town-council of Schaffhausen to build a new bridge over the Rhine, which is there about 120 m. wide; the former bridge had been destroyed by flood water. The bridge built by Grubenmann is known to us from contemporary pictures; already in those days it was well known as a remarkable masterpiece. It possesses, moreover, a special importance in the history of its origin: Grubenmann had, in fact, the unprecedented bold intention to bridge the Rhine by only a single span, for which he had executed a model. The town council did not trust the simple carpenter to execute such a construction which had never been seen before, and forced him to use as intermediate pier the pier of the old bridge which still remained in the middle of the river. Grubenmann apparently agreed and constructed the bridge with two openings, each of 60 m. span, of which we have all details from a model which is still in existence (Fig. 1). He has superposed on the supporting structure of the two openings a third structure in such a manner that the bridge could support itself over the whole width of the river. At the inauguration of the bridge he knocked out the supporting blocks on the intermediate pier, and thus proved that he was able to build the bridge with the longest span then known.

Grubenmann was obsessed with the problem of the long span and we owe this masterpiece of the Schaffhausen bridge to his

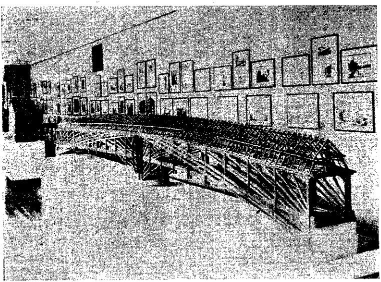


FIG. 1

obsession. The most beautiful memorial to its constructor has been furnished by the famous English engineer Tredgold (1788-1829) in the following sentences: "The French army, in 1799, destroyed the celebrated bridge across the Rhine at Schaffhausen; but the fame of Grubenmann the carpenter will long continue; and the form of that excellent specimen of the art will only cease to be remembered, when carpentry itself no longer exists".

An example which particularly appeals to us because of its tragedy is the "Pont des Invalides" by Louis Navier (1785-1836), the creator of an actual theory of structural statics. Navier had studied, during an educational trip in England, the first suspension bridges which had been built there, amongst which also the famous Menai Straits bridge of the great engineer, Telford. In his report on this journey he has not only investigated and described this structure, but he has also here developed the first correct and detailed theory of unstiffened suspension bridges. The crowning

of his work should be the realisation of the Ponts des Invalides, a suspension bridge with a span of about 150 m. over the Seine at Paris (Fig. 2). This bridge, the first which had ever been designed and executed with the help of a scientifically based theory of statics, was in September 1826 nearly finished after being nearly two years under construction, when under the deflecting points of the retaining chains, cracks occurred in the masonry and some stones were broken. Owing to the accidental coincidence of unfavourable circumstances (death of a contractor, the season of the year, flooding) the relatively small damage could not be rapaired at once and the opposition has had time enough to work against the construction. The Paris town council insisted on the demolition of the bridge. This event was tragic for Navier and shook him deeply, as we can well understand. He himself writes; "Entreprendre un grand ouvrage et surtout un ouvrage d'un genre nouveau, c'est faire un essai, c'est engager avec les forces naturelles une lutte dont on n'est point assuré de sortir vainqueur dès la première attaque". Navier would certainly have won the battle against the forces of nature at the Ponts des Invalides, possibly not at the first attempt, but in any case at the second. He, however, lost the fight against the Paris town council. He died 10 years later, only 51 years old. His work, however, produced good results; even before his death, the French Engineer Chaley built the "Grand Pont" at Freiburg which, with its span of 273 m., remained the wire-cable suspension bridge with the longest span in Europe for nearly a century.

Let us briefly consider in this connection a structure of our times: in 1932 there was inaugurated the George Washington Bridge over the Hudson River at New York, designed by O.H. Ammann with a span of 3500'=1067 m. (Fig 3). An old dream of the bridge builders was then realised; for the first time in history a length of more than 1000 m. had been freely spanned, thus doubling what had formerly ever been accomplished. The design of the Hudson Bridge by Ammann does not show a stiffening truss in its first completion; it is founded on the idea—in the first instance intuitive—that a sufficiently heavy rope is rigid enough in itself without further stiffening parts, to take also the moving live loads without any considerable deformations, and therefore with

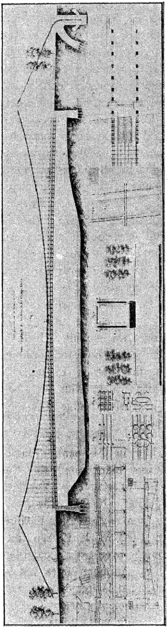


Fig. 2

sufficient traffic safety. Between this idea, however, and the secure knowledge proved by calculation, between the sketchy outlines and



Fig. 3

the working drawings and the execution, there lay many years of very hard work, years of worry and doubt. The realisation of an intellectual conception in a new important structure, which is to be used by thousands of persons with every safety, requires the courage that characterizes famous engineers.

The fact that the realisation of the George Washington Bridge by O. H. Ammann represents a creative deed, is obvious if we consider the former designs for this structure (Fig 4 *a*, *b*, *c*). The want of a bridge across the Hudson River had already been felt for about half a century, but none of the former projects were carried out, though they had all been conceived by leading engineers, because they could not solve the problem of building within economical limits of expenditure.

The execution of such a structure demands the successful solution of a great number of special technical problems in statics and design. I would only mention two points: the manufacturing of the cables of parallel wires required installations, as had never

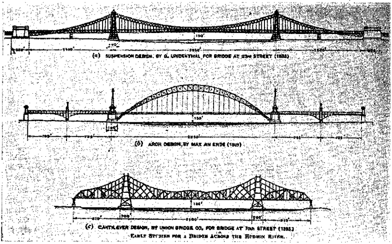

150'
(a) SUSPENSION DESIGN, BY G. LINDENTHAL, FOR BRIDGE AT 23RD STREET
150'
(b) ARCH DESIGN, BY MAX AM ENDE
(c) CANTILEVER DESIGN, BY UNION BRIDGE CO., FOR BRIDGE AT 70th STREET
Early Studies for a Bridge Across the Hudson River.

Fig. 4 (*a*)

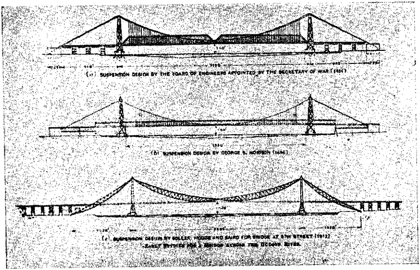

(a) SUSPENSION DESIGN BY THE BOARD OF ENGINEERS APPOINTED BY THE SECRETARY OF WAR
(b) SUSPENSION DESIGN BY GEORGE S. MORISON

Fig. 4 (*b*)

been used before with such productive capacity, and the erection of the towers entailed the use of new erecting methods and effiicient equipment.

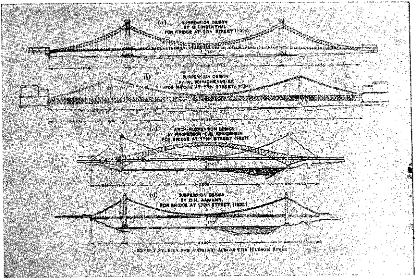


Fig. 4 (c)

2. Regarding the technical side, the conception of the long span is not clearly defined. A reinforced concrete bridge of 200 m. span represents today an excellent piece of work, whereas a suspension bridge of the same span may be considersd as quite a normal construction. Thus the notion of the long span is apparently relative and not absolute.

It is, however, possible to show that, by means of the theoretical weight of a supporting structure we can derive the conception of the so-called "limiting-span", which allows also a technical judgement to be formed of the notion of the long span, above all as regards the economy of execution.

This notion of the theoretical weight shall first of all be derived from the example of a simple truss girder. The total weight G_m of the main girder is obtained from the volume F. s and the weight

per unit of volume γ of the various bars, where however a structural cœfficient μ is to be introduced:

$$G_m = g_m . l = \mu . \gamma . \Sigma F . s = \frac{\mu . \gamma .}{\sigma} \Sigma S . s .$$

We have thus introduced the permissible stress σ as a constant, for example the permissible tensile stress.

By dividing the bar forces into components due to their own load g_m, roadway load g_r and by introducing the unit bar forces S_m, S_r and S_p respectively, we find

$$S = g_m . S_m + g_r . S_r + p . S_p .$$

With relations

$$\Sigma S_m . s = \beta . l^2, \ \varphi_r = \frac{\Sigma S_r . s .}{\Sigma S_m . s .}, \ \varphi_p = \frac{\Sigma S_p . s .}{\Sigma S_m . s .}$$

the factor β depending only on the geometrical form of the system, the factors φ_r and φ_p also on the form of the influence lines and the load distribution, we can write the equation for the weight g_m of the main carrying construction in the form

$$g_m . l = \frac{\mu . \beta . \gamma .}{\sigma} l^2 . (g_m + \varphi_r . g_r + \varphi_p . p .),$$

from which we find, with

$$\alpha = \mu . \beta, \ l_{lim} = \frac{\sigma}{\alpha . \gamma .}$$

the equation of the theoretical weight:

$$g_m = (\varphi_r . g_r + \varphi_p . p) . \frac{l}{l_{lim} - l}$$

If the span length l reaches the limiting span l_{lim} the construction's own load g_m becomes infinitely great, even if the loads g_r and p are very small. Without exceeding the permissible stress σ, the construction is only just able to carry its own weight.

We may imagine the construction factor μ to be composed of three parts: First it has to be considered that the introduced admissible stress σ cannot be fully utilized because of the weakening

effect of rivet holes in tension bars, because of diminution of the permissible buckling stress in compression bars, because of impossibility to suit all sections of the bars exactly to the forces acting on the bars and, in consequence of different rules, also because of the alternating stresses. A second part covers the weight of the gusset plates, butt straps, connecting and diaphragm plates and similar constructional items. Finally, it is—as a rule—convenient to add also the weight of the wind- and cross bracings to that of the main girders, because those elements are necessary parts of the main structure. Practically the construction factor μ may fluctuate between 1·8 and 2·4 and it is a matter of skill of the designer to keep this value as low as possible.

For a single span truss with parallel chords and a chord distance of $h = l/8$ we thus find a value of

$$\alpha = \mu \ \beta_{\cdot} = \text{about } 3{\cdot}4 \text{ to } 4{\cdot}5;$$

and when using normal steel St 37, with a permissible stress $\sigma_{perm} = 1{\cdot}4$ t/cm², we find a limiting span l_{lim} of about 400 to 520 m., the higher value being only attainable by an excellent designer and under favourable conditions.

The formula for the theoretical weight shows that the dead weight of the main supporting construction increases more than proportionally to the increase in span, and we can now consider the question as to what will be the upper span length for which the application of a certain system of supporting structure will prove to be economical. If we agree that the expenditure on half a ton of material to carry one ton of road way and live load is such an upper limit which should in no case be exceeded, we arrive at the conclusion that the *limit of economical application* of a supporting system can be fixed at one-third of its limiting span length. Thus we have found a basis which allows us to form a judgement on the notion of the long span from a technical point of view. For a single span truss, built of normal steel, a span length of about] 150 m. is clearly a long span; it needs an able designer to build such a structure even within the limits of economy which we have stipulated.

The equation of the theoretical weight shows which factors are of importance in order to obtain an economical solution with

a given system of construction. The notion of a limiting span gives us not only an absolute limit for the application of a given system, but it shows also the greatest span length that is economically advisable. The notion of the long span has to be appreciated in a technical economical point of view on the basis of limiting span; this notion thus depends on the form of the supporting system, the quality of material and the skill of the designer. To build a bridge of a single span, there are different possibilities (Fig. 5). Starting from a single girder with full web, by increasing

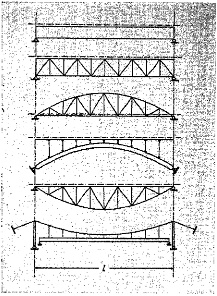


FIG. 5

the height and by replacing the full web by web members, we arrive at the truss system with parallel chords. If we arrange, for example, the upper chord in the form of a parabola, we obtain the parabolic truss, where the chord forces under full load are equal in all panels. If in this system we remove the lower chord and assume that the corresponding forces are taken by the abutments, and if we replace the web members at the same time by giving sufficient rigidity to the upper chord, we arrive at the two-hinged arch with full web. It is very easy to see that, by

eliminating the tension chord, the theoretical weight will be diminished considerably in comparison with the truss system, and the limiting span is increased accordingly.

In the same manner we can imagine that the suspension bridge arises from the truss with parabolic lower chord, the web members being replaced by a special stiffening girder. To carry the reactions of the principal member, the cable, we need here special additional structural elements: the end staying cables and the towers. In spite of this, the limiting span of the suspension system can be considerably increased in comparison with that of the single truss, mainly because the cable can be built of a material with very high tensile strength, namely of drawn steel wires.

3. For the realisation of long span bridges with span lengths of more than 300 m., three systems have been successfully applied, namely the cantilever truss, the two-hinged truss arch and the anchored suspension bridge.

It will be interesting to compare the longest bridges built up to the present according to these systems. It is noteworthy that the cantilever system and not the continuous truss without hinges has been built for long spans (Fig. 6). This is mainly due to

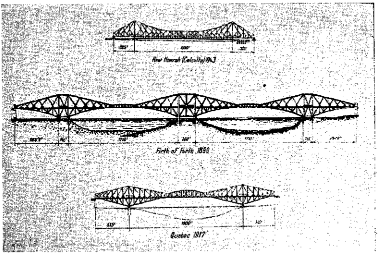


FIG. 6

the fact that by special arrangement of the hinges, by introducing a suspended span of relatively small size, it is possible to influence the distribution of the dead load of the main structure in a very favourable manner, and thus to arrive at a low value of the characteristic β.

The two longest arch bridges executed up to this date are very similar in the form of their system and in span length (Fig. 7);

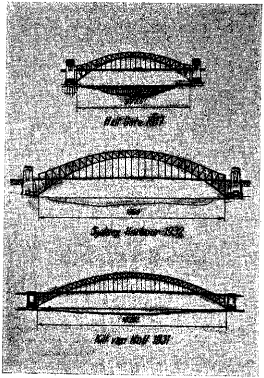


FIG. 7

the Sydney Harbour Bridge built by British engineers shows a somewhat greater height of the system and thus a somewhat more conservative conception than the Kill-van-Kull Bridge (Fig. 8). built by O. H. Ammann and realising the greatest span length of 1675′ = 505 m. of all arch bridges of our time.

The development of the suspension bridge in about half a century can be shown by comparing the venerable Brooklyn Bridge

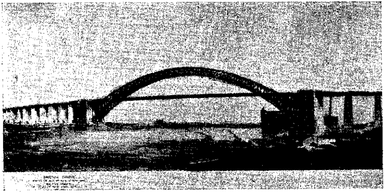


FIG. 8

over the East River in New York, built by John Roebling with a span length of 1595', with the Golden Gate Bridge at San Francisco with a span length 4200' = 1280 m. (Fig. 9). The Golden Gate Bridge surpasses the George Washington Bridge in span length, but not in carrying capacity.

In this series of suspension bridges the Tacoma Suspension Bridge, the third longest of all suspension bridges deserves special mention (Fig. 10). This bridge shows that in the art of bridge building, and especially in connection with long span bridges, there always arise new problems to be solved. The Tacoma Bridge collapsed because of ærodynamic instability in 1940, a few months after its completion. The bridge showed torsional vibrations under no excessively great wind load, so that local parts of the bridge were overstressed, and within a few hours the stiffening girders and the roadway construction collapsed. During the ten years that have passed since this collapse, engineers in various countries have been trying to solve this problem of ærodynamic instability, in order to avoid such accidents in the future. Amongst the research work on this question, the results of a series of experiments by Prof. Dr. J. Ackeret are noteworthy; Professor Ackeret, chief of the ærodynamic laboratory of the Swiss Federal Institute of

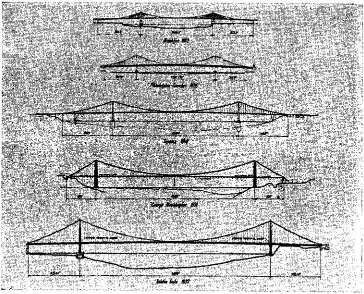


FIG. 9

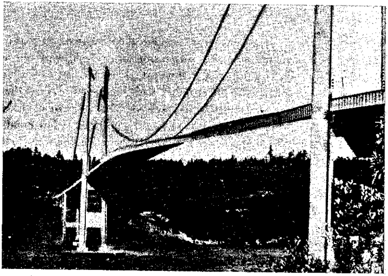


FIG. 10

Technology found that by arranging a longitudinal slot, the danger of this instability can be greatly diminished (Fig. 11). This accident contributes also to our better knowledge of the forces of nature, and thus to development in our art.

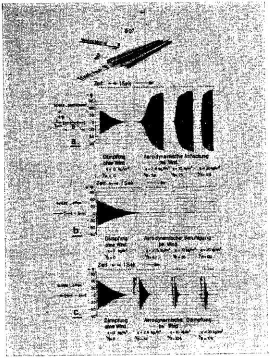


FIG. 11

When we compare the greatest bridges hitherto built with the results of an investigation based on the theoretical weight, say for the conditions of highway bridges ($g_r = 2$ p), assuming for the cantilever and arch systems a high grade steel with $\sigma_{perm.} = 2{\cdot}1$ t/cm², but for the suspension bridges steel wire cables with $\sigma_{perm.} = 5{\cdot}5$ t/cm², the following results are obtained:

The cantilever system with a span of about 500 m. has already reached the economically advisable span length or has even slightly exceeded it. It is a task for the research of the near future to find out whether, by a more appropriate form of the

system, or by better construction of details, the economical span length of this system can be increased or not. For the arch truss, however, the economical limit has not yet been reached by the greatest bridges hitherto built, and it is still economically possible to increase the span length by 100 or even by 200 m. Also for the anchored suspension bridge an increase in span length up to 1500 m. or more is economically possible by the use of parallel wire cables made of high-grade steel wire. The form of the equation of the theoretical weight shows, however, that in general with light metal, for which the relation σ/γ has a higher value than for steel, a further increase of span is possible; the connecting means, for light-metal, however, will first have to be further developed, and the price of light metal in comparison with steel will have to be considerably reduced.

4. In the field of structural engineering the problem of the long span presents itself in a somewhat different form. For those structures, various systems can give good technical solutions; important for the choice of any particular system is always the question of economy. In these cases also it is, for special circumstances, possible to find a successful solution by theoretical reasoning. Permit me to mention only one example: For the new airport building at Kloten a roof construction of 78 m. span had to be designed. It was important not only to find a system with little constructional weight, but also with small horizontal forces, in view of the substructure. The proposal of an unsymmetrical three-hinged arch (Fig. 12) was accepted, because this system showed a reduced horizontal thrust in comparison with a normal arch, due to an increased rise of the compression line. In this system the lower chord is subjected mainly to tension, and the compression forces act chiefly on the upper chord which has a small buckling length and is therefore able to take those forces with steel sections of reasonable cross-section (Fig. 13).

5. The development of the art of steel bridges is not limited to increasing the attainable span length. With even greater clearness, we may mention another tendency of development, if we compare a trussed arch bridge built about 50 years ago (Fig. 14) with a full-web arch of about the same span length built in modern times (Fig. 15). In this field, we can find examples of execution

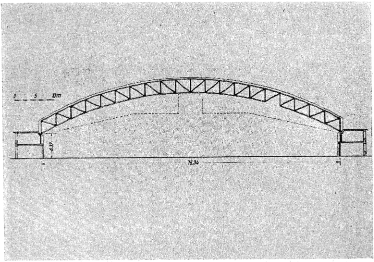


Fig. 12

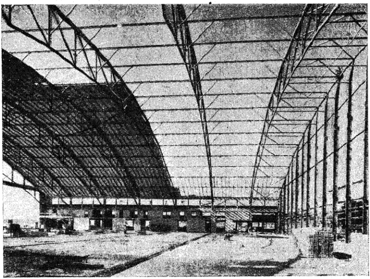


Fig. 13

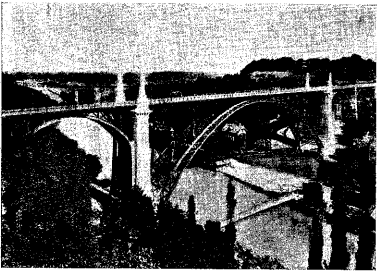


Fig. 14

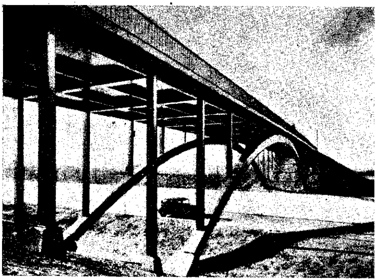


Fig. 15

with the simplest possible arrangement of forms. The same tendency we can find by comparing the view in the interior of an older cantilever bridge with its confusing frame work (Fig. 16)

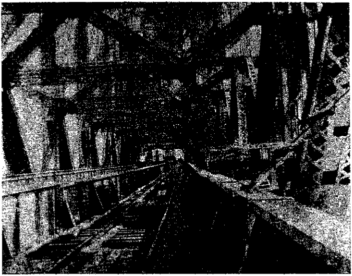


Fig. 16

with the towers of a modern suspension bridge, an example of slenderness and elegance which can hardly be surpassed (Fig. 17). The same tendency to simple and clear forms of construction we can also find in the development of truss bridges. I am sure that this system, with a clear arrangement of web members, will be built also in the future.

The problem of the long span will remain a fascinating one in the future. The span lengths hitherto reached do not mean a limit. In the last few weeks we have been able to read about a design for a suspension bridge across the straits of Messina with a span length of 1524 m., proposed by D. B. Steinman (Fig. 18). In accordance with our theoretical reasoning, such a bridge can be built within relatively reasonable economical limits.

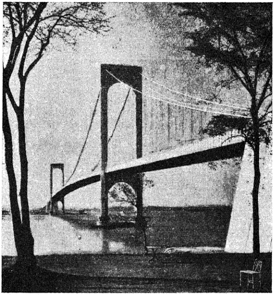


Fig. 17

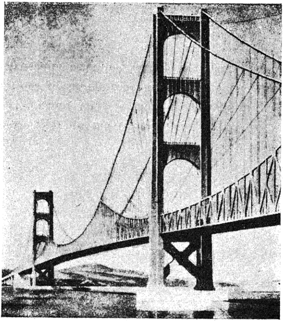


Fig. 18

The successful execution of this bridge will depend on the solution of various constructional and theoretical problems, and thus contribute to the development and the progress of the art of bridge building. From ancient times, the art of bridge building has been a part of human civilisation. The progress made, as measured by comparing the bridges in wood and stone of ancient civilised peoples with the greatest bridges of our times, is mainly due to one intellectual impulse: obsession by the problem of the long span.

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